Low-Cost, Class D Testing of Spacecraft Photovoltaic Systems Can Reduce Risk

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***Abstract* - The end-to-end verification of a spacecraft photovoltaic power generation system requires light! Specifically, the standard practice for doing so is the Large Area Pulsed Solar Simulation (LAPSS). A LAPSS test can characterize a photovoltaic system's efficiency via its response to rapidly applied impulses of simulated sunlight. However, a Class D program on a constrained budget and schedule may not have the resources to ship an entire satellite for a LAPSS test alone. Such was the case with the Lunar Atmospheric and Dust Environment Explorer (LADEE) program, which was also averse to the risk of hardware damage during shipment. When the Electrical Power System (EPS) team was denied a spacecraft-level LAPSS test, the lack of an end-to-end power generation test elevated to a project-level technical risk. The team pulled together very limited resources to not only eliminate the risk, but build a process to monitor the health of the system through mission operations. We discuss a process for performing a low-cost, end-to-end test of the LADEE photovoltaic system. The approach combines system-level functional test, panel-level performance results, and periodic inspection (and repair) up until launch. Following launch, mission operations tools are utilized to assess system performance based on a scant amount of data.**

The process starts in manufacturing at the subcontractor. The panel manufacturer provides functional test and LAPSS data on each individual panel. We apply an initial assumption that the per-panel performance is sufficient to meet the power generation requirements. The manufacturer's data is also carried as the performance allocation for each panel during EPS system modeling and initial mission operations. During integration and test, a high-power, professional theater lamp system provides simulated sunlight to each panel on the spacecraft, thereby permitting a true end-to-end system test. A passing test results in a step response to nearly full-rated current at the appropriate solar array switch in the power system. A metal-halide bulb, infrared imagers, and onboard spacecraft measurements are utilized to minimize risk of thermal damage during test. Data is provided to support test results for both passing and marginal panels. Prior to encapsulation in the launch vehicle, each panel is inspected for damage by the panel manufacturer. Cracked cells or other damage is amended on-site. Because the photovoltaic test system is inexpensive and portable, each repaired panel can be re-verified immediately. Post-launch, the photovoltaic system is again characterized for per-panel deviations from the manufacturer's performance test. This proved especially tricky as the LADEE spacecraft performs only one current measurement on the entire array. The algorithm for Matlab tools to assess panel performance based on spacecraft attitude is discussed.

While not as precise and comprehensive as LAPSS, the LADEE approach leverages minimal resources into an ongoing assessment program that can be applied through numerous stages of the mission. The project takes a true Class D approach in assessing the technical value of a spacecraft level performance test versus the programmatic risk of shipping the spacecraft to another facility. The resources required are a fraction of that for a LAPSS test, and is easy to repeat. Further, the test equipment can be handed down to future projects without building an on-site facility.

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1. INTRODUCTION

The Lunar Atmosphere and Dust Environment Explorer (LADEE) is an unmanned, lunar-orbiting probe designed to characterize the dust environment near the surface and in the atmosphere[1]. The satellite was managed and built at

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NASA Ames Research Center. The $280M mission (including launch vehicle) began with a successful launch in early September 2013 and is will cease its 100-day science operations in spring 2014. The following background on the LADEE satellite and Electrical Power System (EPS) provides context to a specific project risk and mitigation encountered regarding spacecraft photovoltaic system test.

2. LADEE OVERVIEW

LADEE is the first spacecraft built on the Ames common bus; an attempt to streamline small satellite development by using a modular 'bus' approach. Each module forms an octagonal ring of the spacecraft, and modules can be expanded or removed as the design requires. The most basic spacecraft configuration consist of a single 'Bus' (B) or 'Single Stage' (S) module. The Bus module is located at the top of the spacecraft, capped by a radiator panel carrying most of the spacecraft avionics. The Bus module is easily recognized by its trapezoidal sections. The S module, and any additional modules, is built from rectangular sections. The common bus concept is not new within NASA; the strength of the LADEE design is its simplicity and modularity. Initially, LADEE only contained three modules. As the spacecraft design matured, it became evident the spacecraft was not long enough to accommodate the entire propulsion system. The LADEE team simply added a module (the 'Extension' (E) module) and moved on with the rest of the mission. Across the four octagonal modules, two rectangular sections are devoted to payloads, and the remaining 30 to the Electrical Power System (EPS) as solar panels. Figure 1 shows the completed LADEE satellite in transport during launch-site processing.

LADEE Electrical Power System (EPS)

Nearly all LADEE observatory hardware is Commercial, off-the-Shelf (COTS) or based on standard products built by aerospace subcontractors. The entire Electrical Power System (EPS), save for the harness, is consistent with this approach. The EPS is a relatively simple, direct energy transfer, design. No observatory power supply exists. Every payload and avionics unit operates on an unregulated bus voltage that varies with the battery's voltage. Any regulation or isolation is handled internal to each load on the bus. All loads, save for the avionics and communications receiver, are switched on-and-off the bus by a central avionics unit. For generation, LADEE carries 30 body-mounted solar panels; four octagonal modules' worth minus two sections for payloads. The whole array generates 300W, nominally. Individual panels generate about 1 ampere. Sections of photovoltaic power generation system are switched on-and-off the bus as required. Figure 2 illustrates the EPS architecture. Note only a single current-shunt measurement exists for the entire array, and the number of solar array switches (12) is fewer than the available panels. This aspect of the COTS-driven architecture trickled down through design, assembly, test, and flight-operations.

Figure 1: LADEE Spacecraft Hoisted for Encapsulation

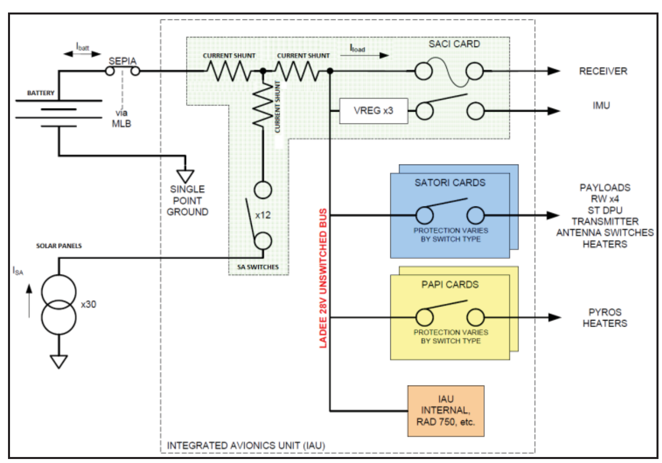

Figure 2: Basic LADEE EPS Block Diagram

The LADEE Orbit—A brief discussion of LADEE's attitude and rotation during the lunar-orbiting science phase (Figure 3) is useful in discussing the design, test, and operation of the power system. In each 113-minute orbit, the spacecraft completes roughly one full rotation. LADEE's octagonal structure means that, in general, only three sides of the octagon will be illuminated at a time. The body-mounted array is cleverly partitioned into twelve segments (one for each switch), such that a failure on a given switch cannot create a catastrophic failure in generation (Figure 4). The need for partitioning is driven by the COTS circuit card design. The combination of segment-to-switch mapping, direct transfer bus, and non-deployable, non-adjustable arrays translates into the need for an end-to-end EPS test fixture that can easily rotate around the spacecraft, generating light and verifying response.

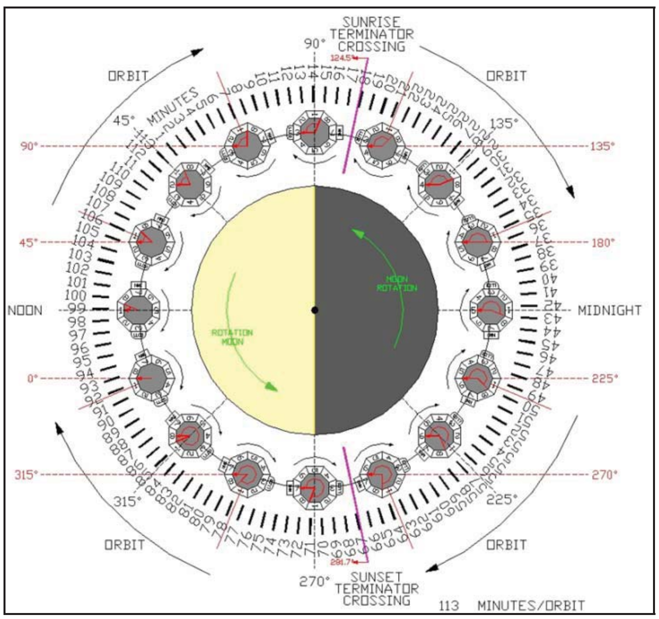

Figure 3: Typical LADEE Science Orbit

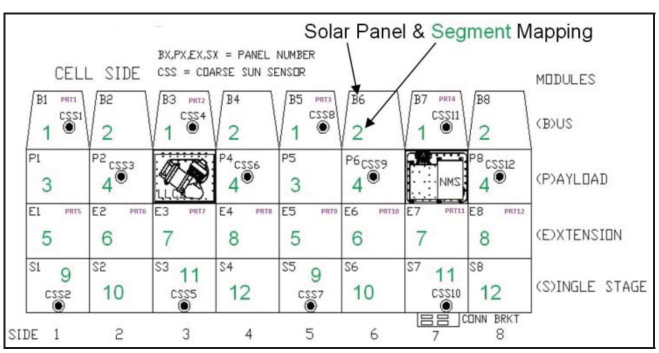

Figure 4: LADEE Solar Panel-to-Switch Mapping Permits Graceful Degradation

3. LAPSS AND RISK

What is a LAPSS?

A Large Area Pulsed Solar Simulation (LAPSS) test is generally considered the industry standard for characterizing performance of solar cells, panels, and photovoltaic systems. The test consists of a set of lamps with bulbs matched closely to spectrum of sunlight. In the case of satellite applications, the intensity and spectral emittance is adjusted to that in the space environment. The actual test application is a sequence of light pulses, so as to achieve an impulse response and efficiency of the unit under test[2]. The brief application of light also guarantees little or no thermal stress applied to the solar cells. LAPSS testing can be performed by the panel manufacturer during evaluation, as was the case for the LADEE units. At the observatory level, a LAPSS test can substantially reduce risk by proving the functionality and performance of the power generation subsystem. The array efficiency can be estimated to a level of precision sufficient to detect non-visible cell defects, critical for long-lifetime arrays.

LADEE, Risk, and Requirements

The original LADEE environmental test baseline included transfer to another NASA facility with numerous capabilities, including an observatory-quality LAPSS system. Originally, the project held risk #LADEE-87:

> Given that LAPSS testing will be performed at the vendor, then at observatory-level testing, there is a possibility that late discovery of a solar panel issue will cause a late schedule and cost impact. Since LAPSS testing facilities do not exist at ARC, there is a concern that panel damage may not be discovered until observatory-level (LAPSS) test.

Figure 5: LADEE-87 Risk vs. Time

Initially, the project was rightly concerned about the lack of ability to detect solar panel damage prior to the observatory level LAPSS test. Both risk #LADEE-87 and the team's risk posture morphed during Phase D. As the project matured, the environmental test baseline changed to a subcontracted approach[3]. The combination of competitive vendors, their cost, available facilities, and diminished schedule reserves resulted in a final selection lacking LAPSS capability. Further, as LADEE entered Phase D, its definitions of risk consequences shifted to accommodate shrinking schedule reserves (Figure 5, Tables 1, 2). These factors combined to redefine and elevate risk #LADEE-87 from 25th to 3rd in project ranking:

> Given that LAPSS testing was only performed for each individual solar panel by the vendor, there is a possibility that without observatory level photovoltaic system testing, the requirements verification of the 295 Watts solar panel output power (EPS-4) will not be verified by test.

The EPS-4 generation requirement text reads as follows:

> At a Beta Angle of 0 degrees, after exposure to the space environment in a lunar orbit for 6 months, the minimum total array output including all degradation factors excluding shadowing shall exceed 295W at a design voltage of 34V, 80°C[4].

Table 1: Original LADEE Risk Definitions

Rank	Likelihood	Cost	Schedule	Performance
1	< 1%	< 0.8%	Negligible	Negligible
2	1% to 10%	0.8% to 1.5%	≤ 1 months	Minor
3	10% to 33%	1.5% to 2.5%	1 to 2 months	Moderate
4	33% to 50%	2.5% to 4%	2 to 4 months	Major
5	> 50%	> 4%	> 4 months	Blocker

Table 2: Phase D LADEE Risk Definitions

Rank	Likelihood	Cost	Schedule	Performance
1	< 1%	< 0.8%	Negligible	Negligible
2	1% to 10%	0.8% to 1.5%	1 to 2 weeks	Minor
3	10% to 33%	1.5% to 2.5%	2 to 4 weeks	Moderate
4	33% to 50%	2.5% to 4%	4 to 8 weeks	Major
5	> 50%	> 4%	>8 weeks	Blocker

4. MITIGATION

Addressing the Risk

From the power system team's perspective, the risk to requirement #EPS-4 was secondary to the lack of a proper end-to-end power generation subsystem test. The solar-panel manufacturer already performed LAPSS testing on individual panels[5]; the compiled results of which exceed the EPS-4 requirement. The spirit of the risk was that even though each component of the subsystem passed its respective testing, the system as a whole is greater than the sum of its parts. Specifically, the EPS team cited the following possible causes of system-level failure:

- Incorrect or swapped solar panel connectors. Will manifest as mis-mapping panels to solar-array switches.
- Damage or degradation to the COTS PCB carrying the solar array switches.
- Proper harness connections, but corrosion or degradation leading to an increased harness resistance. Would only manifest at higher currents and lead to a power loss or shift in the panel's current 'knee.'
- An individual string within a panel is degraded, damaged, or failed following delivery and installation.
- A software bug in the code driving the solar array switches. Will manifest as closing a switch to the wrong solar array segment.
- Improper connections or software for measuring the PRT temperature sensors embedded in selected solar panels.
- Improper connections or software for measuring the Coarse Sun Sensors embedded in selected solar panels.

Obviously an on-site LAPSS facility would address these concerns, but the cost (~$100k) and months to construct and calibrate were simply not available. Even if it were available, a singular LAPSS test has limitations of its own. Subsequent panel damage due to handling may not be revealed until post-launch. The two months to ship the spacecraft and perform the test are costly and risk-prone. The EPS team therefore needed a low-cost, quick-turn approach. A review of the detailed risks reveals none is particularly sophisticated or necessitating high technology. Most are related to functionality only, and the performance requirements do not imply that efficiency characterization is even necessary. Therefore, a LAPSS facility would be overkill. The team simplified the process by making a key decision:

- Formally verify requirement #EPS-4 using the manufacturer's per-panel LAPSS test data.
- The test results are consistent across each panel type, and will also be used for system modeling and initial mission operations allocations.

The general process for an end-to-end test can now be boiled down to the following basic flow[6]:

1. Set up a lamp aligned with the center of a single panel at a safe distance from the panel.
2. Configure the avionics' software to open all solar array switches, save the switch and segment associated with the panel under test.
3. Warm up the lamp (covered) for one minute (nominal)
4. Quickly remove the cover, and record the spacecraft solar array current.
5. Continue to illuminate the spacecraft, monitoring current and temperature until the system stabilizes. Abort if safety limits are violated.
6. Power off the lamp.
7. Move the lamp to the next panel and repeat the process. Maintain the same lamp configuration and distance for consistency.

Selecting and Tuning the Lamp

Picking the lamp system was largely driven by the type of bulb required; it and subsequent tuning required the most engineering effort in the activity. Initially, the LADEE team used a small, handheld halogen lamp. Unfortunately, the panels only generated about 30mA using this light, or 3% of their rating. The initial impulse was to simply find a higher wattage lamp. On further investigation, the spectrum generated by halogen is not the best solution for testing solar panels. Sunlight, especially without atmospheric attenuation or distortion, can be approximated by Planck's blackbody equation[7]. Any man-made bulb will differ from the ideal sunlight spectrum to some degree; however, a halogen bulb will tend to generate less UV and more infrared than sunlight. This translates into less energy transformed to current, and more energy manifested as heat. Therefore, a very high power halogen lamp is required to generate current close to a panel's rating, at the risk of overheating the panels. That said, halogen is attractive as a solution in that many inexpensive and portable COTS options are available. Further research into theatre lighting revealed metal-halide lamp systems as another option. Specifically, metal-halide bulbs are typically used in high-power theatre lamps sold as 'sunlight' lamps. These lamps are designed to simulate sunlight for indoor filming or photography.

Fortunately, lamps of this type are easily rented by theatre supply houses. The EPS team rented a couple lamps at a relatively inexpensive rate (~$750 per week) and ran experiments on a flight qualification panel (Figure 7). Relatively few NASA engineers are theatre lighting operators; the qualification (qual) panel was ideal for this experiment. The qual panel is a factory-tested unit from the same lot as the flight panels; any results translate easily to the spacecraft test. Being a non-flight spare panel, testing can occur outside of a cleanroom environment, with plenty of space and no major concerns regarding damage or degradation. The team built a panel test fixture and mounted the whole assembly to an optical bench. Connections were provided measuring current and embedded-sensor temperature (Figure 7). Testing involved iterative adjustment of the following lamp-configuration parameters, finalizing on the following settings for test[6]:

Table 3: Lamp Configuration Parameters

Parameter	Value for Flight Test
Height	Varies based on spacecraft orientation. Align with panel center.
Distance to Panel	No closer than 36 inches.
Lamp Focus	Roughly 15% spot for 25% de-rated current
Illumination Time	1 minute warm-up with scrim cover installed, followed by up to 3 minutes with scrim removed

Figure 7: Experimenting with the Qualification Panel

The team settled on an 1800W, Hydgragium Medium-arc Iodide (HMI; i.e. metal-halide) lamp system, with ballast and adjustable stand. Figure 8 shows the lamp spectrum over laid with a 6000K blackbody spectrum[7][8]. The total purchase price for the system is $11k with a three-week lead time.

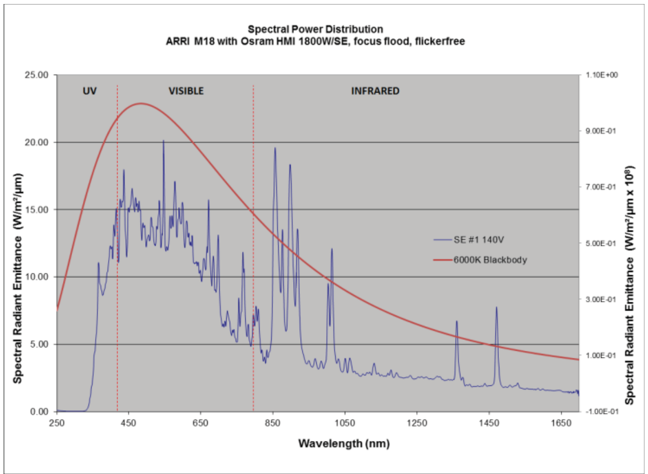

Figure 8: Test Lamp Spectrum[7][8]

Selecting the Current:

The amount of current required for a 'passing' test was the matter of some debate. Ideally, the maximum panel current would be generated so as to meet the EPS-4 requirement by test. However, the theatre lamp is not that precise; slight variations in warm-up time, distance, and focus can produce large swings in panel current. The lab experiments also showed that some cases can generate currents in excess of the design value. To eliminate risk of hardware damage, the flight test requires[6] a minimum of 500mA generation, and a target of 80% of the manufacturer's LAPSS measurement. This value is large enough to expose any substantial power losses in signal path, and to cause a failed string to clearly result in an out-of-family measurement.

Hardware and Personnel Safety:

Thermal—In addition to safely de-rating the current generation, several safety aspects required resolution prior to the first flight test. Though the metal-halide bulbs better approximate the sunlight spectrum, they still generate infrared. Both the panel and surrounding flight hardware require real-time monitoring to prevent thermal-related damage. Only 40% of the LADEE panels carry embedded temperature sensors. To maintain hardware safety, the test requires use of a calibrated, handheld thermal imager. The specific imager used (Fluke Ti25) is essentially an infrared digital camera. The entire panel can be monitored and saved for offline analysis. The test limit for panel temperature is 70º Celsius, driven by the mounting bushings. This proved good for nominal safety measurements, but limited for precision use due to surface reflections.

Contamination—LADEE is a contamination-sensitive mission due to the presence of mass-spectrometers and optical instruments. All spacecraft activities occur in 10k clean tent, and instruments are continuously bagged and purged. Theatre lamp systems are not necessarily designed for a clean-room environment. The rental lamps see heavy usage, and often have peeling paint. New lamps outgas substantially, and must be burned in prior to test in the clean tent.

Optics—Though the lamp is, roughly-speaking, meant to simulate sunlight spectrum and intensity, most of the optical hardware on the spacecraft is not designed to look directly into the sun. LADEE's body mount panels are right next to the payloads; for protection, all instruments were shielded with reflective blankets. LADEE's star trackers can withstand sunlight, and did not require protection.

Personnel Safety—Regarding personnel safety, precautions were necessary. One of the strengths of the metal-halide bulb is less infrared and more UV; unfortunately human eyes are sensitive to UV radiation. Further, the light reflects easily and can cause headaches even when personnel avoid looking at the bulb. Fortunately, an inexpensive, stock solution was available. Most standard safety glasses meet the ANSI Z87.1 standard for UV protection. Welding glasses also meet the standard, and often provide fitted, wrap-around protection. To meet personnel safety, the project purchased a dozen glasses and required[6] all personnel to wear them during test. Debriefs and placards serve to notify all staff.

5. TEST RESULTS

The first test occurred just after final observatory integration, and was straightforward to execute. The test time was about four hours, and required three staff to operate. The EPS-4 295W requirement was not met due to de-rating. Figure 9 shows a time series of all currents, embedded panel temperature and coarse sun sensors. Figure 10 shows a typical 'step' current signature for each panel type. Note the signature shows evidence that the lamp warm-up persists beyond one minute. All panels measured above the 0.5A requirement, with most between 70-75% of maximum. Typical panel temperatures hovered around 45º Celsius (Figure 11), with the hottest at 59º Celsius. The test was considered a success, and LADEE Risk #87 was subsequently closed.

LADEE project management was sufficiently happy with the test that it approved purchase of a new lamp system. The test proved to be simple enough in execution that the test rig could be taken to the launch site for evaluation prior to encapsulation. At the final observatory test (Figure 12),

the team attempted verification of the 295W requirement, with good results (Table 4).

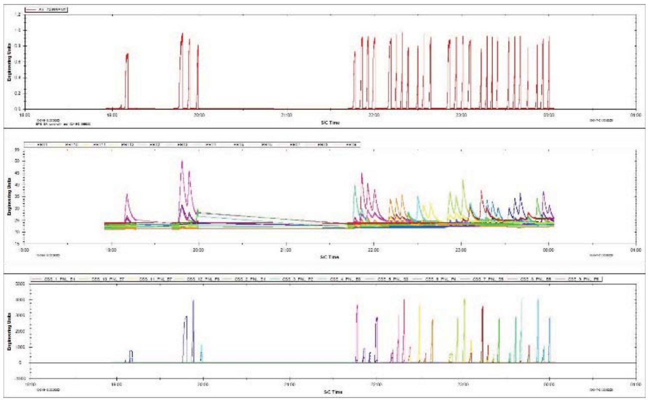

Figure 9: Solar Array Test currents (top), embedded temperature sensors (middle), and coarse sun sensors (bottom)

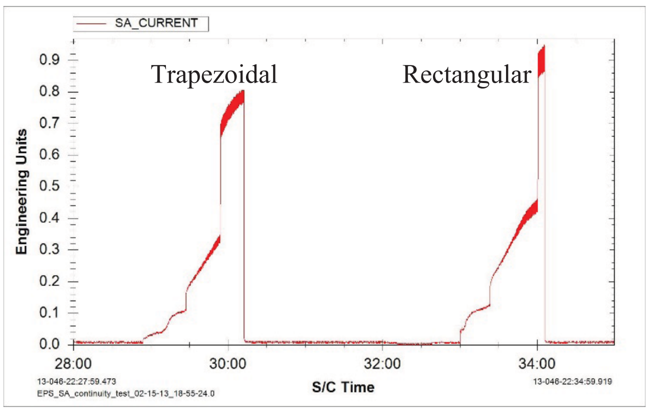

Figure 10: Typical Current Signature

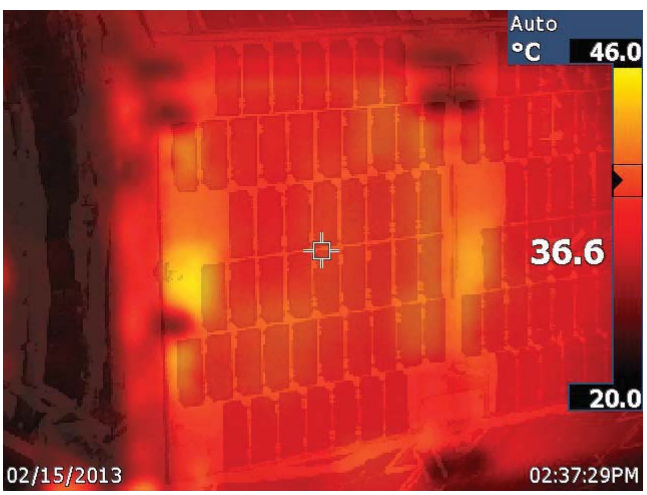

Figure 11: Infrared Image of a 'Normal' Illuminated Panel

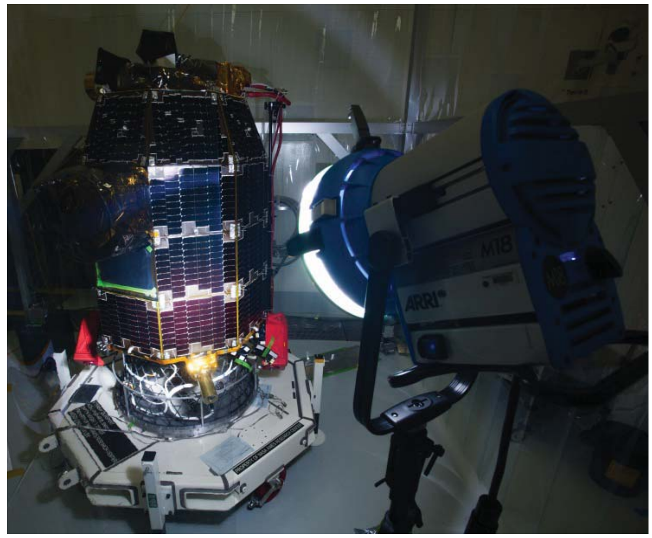

Figure 12: LADEE Under Test

Table 4: EPS-4 Nearly Closed by Test

Minimum Power	Maximum Power	Average Power	Requirement
270.9W	339.7W	310.4W	295W

6. Maintenance, Inspection, and Repair

Receiving Inspection

To maintain the low risk following test, the LADEE team used tried and true methods of visual inspection and record keeping. The initial delivery of hardware to NASA ARC and participated in an on-site inspection. The team used this visit to document the initial state of the hardware. Periodically during Integration and Test (I&T), the LADEE team performed their own visual inspections of the hardware. This best practice resulted in the discovery of two panels with minor damage.

Launch-Site Inspection

Following shipment to the launch facility (NASA Wallops Flight Facility, Virginia), the manufacturer performed an on-site inspection and repair of the panels. Roughly 15% of the array was found to have minor cracks and damage due to handling (Figure 13). During an extended stay at Wallops Island, the repair team was able to fix all affected panels with no issues (Figure 14). The simplicity, portability, and ease of operation of the lamp test fixture made it easy to re-evaluate all repaired panels prior to launch. Note the inspections and final test were not part of the project's original (observatory-LAPSS test) plan.

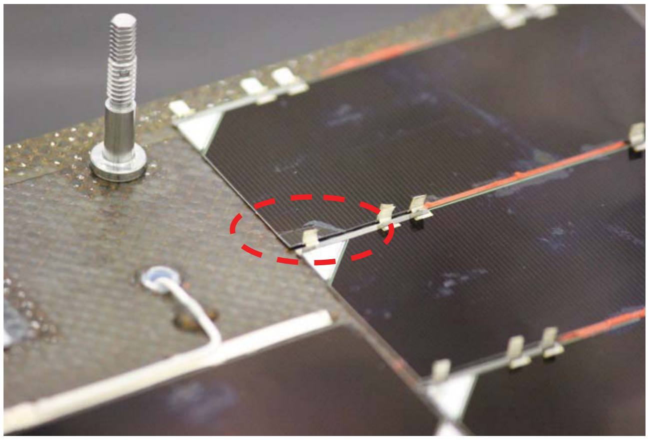

Figure 13: Damaged LADEE Solar Cell

Figure 14: Cell Repair at the Launch Facility

7. Mission Operations

A major assumption that enabled the entire risk mitigation process was the allocation of manufacturer's per-panel LAPSS data for requirements verification, LADEE EPS modeling and mission operations tools. Several factors can invalidate that assumption. One, obviously, is any damage and repair that could occur prior to launch. Another is degradation; though LADEE is a short-lifetime mission, some level of radiation or micro-meteorite damage will occur. A final factor, shadowing, is less a function of the panels themselves than the spacecraft geometry. Protrusions in the spacecraft will tend to shadow portions of the array, and predicting that behavior can be extremely complex. Neither the lamp test nor a LAPSS would completely account for shadowing. All of these factors feed into the need to continuously evaluate the health and performance of the solar array through mission operations. This would be relatively simple if the spacecraft's COTS avionics measured current from each panel, or even each switch. Unfortunately this is not the case; only one measurement is made for the entire solar array system.

During Operational Readiness Training (ORTs), the LADEE EPS team developed a method to evaluate panel performance throughout the mission. The approach illuminates the interdisciplinary nature and value of mission operations experience, even for the hardware designer. The solution lay in the discovery that the Guidance, Navigation, and Control (GNC) system calculates and stores the spacecraft sun vector as part of its attitude determination process. As mentioned, the EPS subsystem records the solar array current and number of closed switches. The tool simply combines the downlinked sun vector with the EPS data and a geometrical spacecraft model to determine an expected array current, and the derived error (Figure 14). Observation of the spacecraft over a combination of attitudes can be used to back out the behavior of individual panels, thereby updating the manufacturer's data.

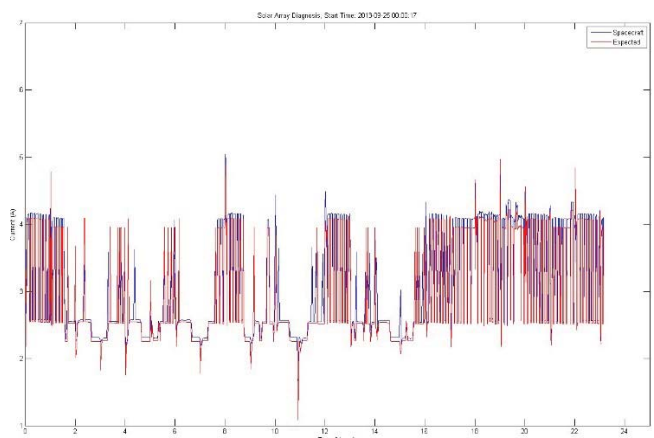

Figure 14 – Mission Operations Tool Overlays Expected and Actual Generated Array Current

8. Conclusions

The LADEE program applied true Class D risk tracking and mitigation techniques to address a major technical risk. A project decision driven by resources, combined with redefinition of risk metrics, forced its staff to reconsider standard practices and determine what was really necessary. The process of test research development, execution, and risk closure took roughly 10 weeks (Figure 5). The total cost was roughly 12% of the industry-standard (LAPSS) solution in materials costs, and 12 labor-hours per test. Further, the theatre-lamp approach is easy to train with and portable. When combined with standard visual inspection, it actually added value over the LAPSS approach in this

application. The test proved the system met power generation requirements 6 weeks prior to launch. Post-launch, interdisciplinary approaches proved useful to track performance of the array in flight. Finally, the entire approach can be easily handed down to future missions.

ACKNOWLEDGEMENTS

This work was performed under the direction of Joseph Camisa, who served as the LADEE EPS Lead until his retirement in mid-2013. Additional notes of appreciation go to the NASA GSFC Power Group (Code 563), the Emcore inspection and repair staff, and the LADEE Systems Engineering, Project Management, and Integration and Test teams for their participation in this work.

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BIOGRAPHY

Josh Forgione *received the B.S. degree in electrical engineering from Virginia Tech in 2000. He joined NASA in 2002, first at Goddard Spaceflight Center (GSFC) and then Ames Research Center in 2007. Josh's hardware deliverables are currently flying on the Aquarius/SAC-D satellite, the NASA ER-2, Global Hawk, and WB-57 aircraft, and multiple airborne instruments. He joined LADEE in 2011 and currently serves as the LADEE Electrical Power System lead through mission operations. His interests span electronics and electrical systems, particularly on analog design for scientific instruments and power systems.*

Gilbert Kojima *was born in Honolulu, Hawaii, in 1949. He received the B.S and M.S. degrees in electrical engineering from the University of Hawaii, Honolulu, HI, in 1971 and 1974, respectively. He is began his career at NASA, Ames Research Center (ARC), Moffett Field, CA, as a physicist, then as an electrical/electronics engineer. During his career at ARC, he has designed and developed numerous electronic instruments and major electrical control systems to support the diverse array of research and development activities at NASA. One of his major career accomplishments was as the principal tunnel conditions controls engineer for Unitary Modernization Project. His interest includes anything new and challenging involving electrical/electronic design.*